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Recent Developments in the Safety Assessment of the Colosseum

Études récentes de l'évaluation de la sécurité du Colisée

Entwicklungen in der Sicherheitsbeurteilung des Kolosseums

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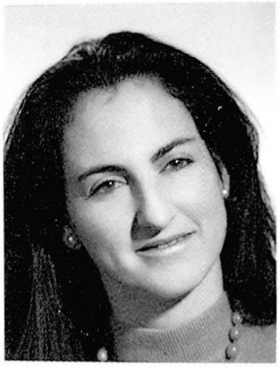

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SUMMARY

For ten years the Colosseum has been the object of interdiciplinary research aimed at assessing its overall and partial structural behaviour and safety level. Studies of the documentation, in situ observations and analytical modelling have allowed us to understand why the collapse has been asymmetric and why the failures, always originating from seismic actions, sometimes occurred decades or centuries after the recording of the earthquake. In this paper the results are discussed and the weakness of the monument with regard to earthquakes is outlined, the zones requiring strengthening and are outlined and the general theory underlying the interactive design is presented.

RÉSUMÉ

Au cours des dix dernières années, le Colisée a été l'objet de recherches pluridisciplinaires afin de comprendre le comportement structural partiel et global et d'évaluer les niveaux de sécurité. L'analyse des documents historiques, les observations in situ et la modélisation ont permis de comprendre les raisons de l'effondrement asymétrique et des affaissements, toujours causés par des actions séismiques, lesquels se sont produits parfois des décennies ou siècles après l'enregistrement de séismes. L'article décrit les résultats obtenus, la faible résistance du monument aux séismes, les zones nécessitant un renforcement ainsi que la théorie générale du projet d'intervention.

ZUSAMMENFASSUNG

Seit zehn Jahren war das Kolosseum Objekt pluridisziplinärer Forschung, um das teilweise oder gesamte Verhalten der Struktur zu verstehen und das Sicherheitsniveau zu bestimmen. Durch Studien der Dokumente, in-situ-Beobachtungen und analytische Modellierung wurde eruiert, warum der Kollaps asymmetrisch geschah und weshalb Kollapse, immer durch Erdbeben verursacht, manchmal Jahrzehnte oder Jahrhunderte nach dem Beben erfolgen. Dieses Dokument beschreibt die gewonnenen Erkenntnisse, die Schwächen des Monuments, was Erdbeben betrifft, die Zonen, die eine Verstärkung erfordern, und stellt die gesamte Theorie des Interventionsprojektes vor.

1. INTRODUCTION

This study was initiated for the double pourpose of discovering the actions that caused failures in the past and how the collapse mechanisms developed, and of assessing the safety of the current configuration, this leading to the most convenient design of the repair and strengthening required against earthquakes.
The complexity of the structure and the various events that it underwent over the centuries oblige us to follow different approaches which take into account both subjective and objective aspects. Where the former are related to the interpretation of the history of the monument and the observation of the present state of the building, the latter concern in-situ survey, assessment of mechanical features and structural analysis through mathematical models. As it will be seen, it is actually only through a feed-back procedure of exchanging information between the two areas that the structural meaning of the historical notes can be correctly interpreted and the analytical models relate to the real situation [1].

2. THE HISTORICAL STRUCTURAL BEHAVIOUR

The construction of the Colosseum probably began in 72 a.D. and lasted almost ten years, the monument being dedicated under Titus reign in the 80 a. D.(fig. 1). One of the hypotheses that explains the rather fast realization of the monument is that the building-site was probably organised in four portions divided along the principal axes of symmetry of the plan. The connections between these portions can then be regarded as the weak points in the masonry. A second reason of amorphism is the building site, previously partially filled by the lake of the Domus Aurea, created by an alteration of the original hydrography settlement. The topography and the few available non-destructive drillings, it can be seen how the slopes on the two sides of the major axis have different gradients and soils: the mechanical behaviour of the ground beneath the structure is therefore not homogeneous and the foundation system presents variable depth and lay-out.
The first analitical model is a test of the structural original capacity of the monument under the dead load action. The f. e. model realised with 8 node-brick-elements, which best simulate the shear behaviour of the stone blocks, covers the three annular bands connected by the annular vaults, while the inner radial brick-masonry walls are neglected due to the high number of d.o.f involved. Under static conditions (fig. 2) the bearing capacity basically relies on the pillars whose average stresses vary from 23 KN/m^2, at the base of the first order, to 10 KN/m^2 at the base of the third order. A slightly flexural effect is also present due to the global circumpherential shape that does not completely absorb the thrust of the annular barrel vaults, causing a stress increment of 15% at the second order in the pillars close to the major axis of symmetry, where the radial component of the arches' thrust is maximum. The stress in arches and vaults is at least two order of magnitude lower than that in the columns and it can therefore be said that the monument is overdimensioned for static loading, even if we refer to the crowd load during the "spectacula", the failure stress of the travertino material being 500 KN/m^2, while the masonry limit stress, due to the roughness of the contact surfaces and the weakening due to the dressing of the stone, is definetely lower.
The natural events that followed the construction during the first centuries were not dangerous enough to compromise the safety of the monument even if fires, small earthquakes and floods certainly contributed in locally lowering the strength of the materials. Among others we only note here the fire of the 217 that destroyed the timber structure of the top roof. The first destructive event was the earthquake in 443, estimated of VIII-IX grade Mercalli Scale, with the epicentre in the roman region. The Colosseum suffered damages in the seating area, the arena, the podium and at the attic level. Some of the gigantic columns of the attic level fell down into the cavea and the damages were so serious that it took three consulates to be restored. Some of the works can still be seen at the top of the external wall, where a chaotic cyclopic masonry was set.
In order to identify the structural behaviour of the monument under seismic actions a second set of models of the original configuration has been analysed. The analyses are spectrum response dynamic elastic and, due to the dimensions of the overall mesh (46568 d.o.f.), the model has been divided in two halves along the principal axis and subjected to a seismic force acting along the dividing axis.
Two orders of problems arise; The first is related with the quantification of the seismic action that does not come straight from the M.S. information recorded. Examining the historical data regarding the seismic events recorded in the area it can be seen that an earthquake of VIII-IX grade has a return period of about 500 hundreds years. Giuffrè et al.[2] assessed that a Richter intensity of 6.68

can be attached to such period and therefore a ground acceleration of 0.05-0.06 g can be deduced. Evaluating the amplification of the masonry structure up to 2.5-3 times a design value of 0.15 g is obtained. It is worthwhile noting that the maximum seismic amplitude stated by the Italian Seismic Code for the III category areas is 0.16 g, Rome not being considered seismic area.
The second question is the interpretation of the results obtained with the hypothesis of elastic behaviour, while the structure over a certain stress level presents a strong dissipative behaviour due to friction between the blocks; on one hand, tensile stresses are feasible only in the case of a quite high compressive orthogonal stress level , on the other end the peaks produced by the elastic models are probably never attained due to the sliding and dissipation of energy that takes place at the contact surfaces. Nevertheless this type of analysis is still very valuable in defining the behaviour up to the elastic limit and in identifying the weaker and most stressed elements of the structures, and in evaluating the global collapse mechanisms. The stress and deformation values, given below, must be taken as indicative, referring to macro-elements that simulate extensive portions of the blockwork.
The cylindrical vertical surfaces (figg. 3-4) exerted a fundamental bidimensional behaviour which, as long as the friction limit is not overcome, lead to relatively low bending moments in the pillars: the maximum reaches 13.0 KN/m^2 that added to the dead load stress gives a top value of 36 KN/m^2 while the cross section is wholly compressed. On the other hand, in the upper part, due to the low vertical stress level and the lack of radial constraint, active in the lower part by means of the annular vaults, the friction limit is extensively overcome: tensile circumpherential stresses (σ_a) reach upto 4.53 KN/m^2, while the corresponding vertical stress (σ_v) is 6.6 KN/m^2 with a ratio 0.68 that is over the value of the dynamic friction coefficient $\mu = 0.433$, corresponding to the fact that the most severe damage occurred here.
The f.e. analysis further confirms that a single event of this magnitude cannot have taken the structure upto complete failure but can only have caused localised damages: distribution of stresses along the plan are not, infact, homogeneus and only arise to limit values on one or two radial alignments. Furthermore limit stresses do not take place on the same alignments for all the elements. This means that other causes and factors must be investigated in order to explain how the first vertical solution of continuity occurred and whether from there the collapses extended to a big portion of the structure. Again the analysis of the historical information may prove valuable for this purpose.
The next destructive earthquake recorded is in the year 801; it arrived after a period of almost 300 years during which, the monument was not only disused and abandoned (after 523) but also a few small earthquakes occurred, plant roots expanded existing cracks and formed new ones and finally, the structure underwent serious damage when the metal connections between blocks were removed. The earthquake probably had its epicentre in the Abbruzzese Appenino and caused damages up to the IX M. S. grade in the roman area. Extensive notes of the damages in the Colosseum are not available but it can be inferred that what was left of the cyclopic order at the attic level fell into the cavea causing huge damages in the inclined barrel-vaults of the arena, and other less striking structural cracks. It is likely that on this occasion the first important breach in the annular walls opened (fig. 5): if the location is deduced from later iconography (there being no remaining contemporary iconography), we can say that it occurred in the quarter overlooking the Constantinus Arch, this being common to all the available views. Whether it has occured at a point closest to the major or minor axis of symmetry can not be positively said, but our results indicate the portion close to the major curvature as the one with highest radial tensile stresses in the annular vaults (up to 3.25 KN/m^2 versus 2.66 KN/m^2 along the minor axis) and highest annular stresses in the attic wall, 5.6 KN/m^2 with a vertical compressive stress of 5.2 KN/m^2, that clearly exceed the frictional resistance. Once the sliding occurs there is a corresponding increase in the circumpherential length at the upper level leading to out of plumb and thus to relevant eccentricity of the normal force in the first order pillars, consequent reduction of the effective section, and finally an increase of stress level, which initiate instability.
In that occasion, with the extensive damages of the cavea's barrel-vaults, the radials connections also started weakening. As seen from the model, in the original state the annular vaults perform a fundamental role transmitting stress between inner and outer portions, in this way limiting flexural stress in the outer pillars. This bond was further released when during the X and XI centuries the noble families of the city started fighting for the possession of the Colosseum and eventually fortified it, destroying the original staircases (which may have been partially destroyed already) and opening holes in the annular vaults to put removable ladders between the floors. The medal of Ludwig The Bavarian, minted in 1328, depicts the monument with the upper ring closed, but the occasion of the representation, commemoration of the new emperor, and the small scale of the picture can explain

the lack of reliability. However this is the last known iconographic document before the destructive earthquake of 1349. Minor earthquakes of local origin had in the meanwhile occured in 1255, 1287, 1300, 1321 and in 1348, but none of them caused as much destruction as the one of September 1349, with epicentre in the Umbro-Abruzzese Appenino, which was very violent in l'Aquila, Montecassino and Perugia. Damages in Rome affected the S.Paolo and S.Giovanni basilicas, and caused the complete failure of the Torre dei Conti and Torre delle Milizie. This is thus remembered as the most destructive earthquake ever in Central Italy.

As for the Colosseum, all historical sources agree in recognising this as the event that produced the complete failure of the two external cylindrical walls on the Celio side. It has been said that the structural configuration had changed significantly since the origin and had, infact, become weaker, due to the relaxation of the block-work and the beginning of out of plumb phenomena, locally amplified by constructive defects (fig. 6). If this explains the more destructive effect of this earthquake compared with the previous ones, it still does not explain why the distribution of failures was not spatially homogeneus but concentrated on the Celio side. The reason may be found in the foundation system. More accurate studies will be required in order to assess the actual situation, the simulation of a different stiffnesses at the foundation level, by means of spring finite elements with variable stiffnesses, evaluated taking into account both the mechanical characteristics of the ground and the geometry of the foundations, helped to give a better understanding. The spectrum dynamic analysis produces smaller natural frequencies and higher amplification on the Celio side (fig. 7), the most important modes showing rotational symmetry. As for the stresses they reach a maximum in the inner pillars (with a maximum of 27.5 KN/m2) of the more flexible side, while the effect of different foundations decreases at the upper levels. If we add this value to the dead-load value we find that tensile stress is reached in a wide portion of the section, evntually causing crushing on the other edge. Even if we might initially assume that these actions were partially redistributed among the pillars and the inner brick walls, we have just seen how the historical events released radial collaboration, and while the inner pillars could benefit from it, the medium and outer ones definetely could not, their stress levels increasing upto collapse.

After this earthquake the Colosseum was abandoned apart for its use as a quarry for travertine blocks and loose bricks for use in furnaces. During the next three centuries, all sources agree in stating that most of the material that was taken for other building sites, apart from a few recorded exceptions, was not removed from the structure itself but from a large mound of rubble called "Coxa Colisei". Also in this period (beginning of the XVI century) the ruin of a wide portion of the inner ring on the Celio side around the minor axis is recorded. Other "spontaneous" failures took place in 1646 and 1689. These events, called "spontaneous" because they cannot be directly related with any seismic action, can be explained as consequences of the mechanism described above: the high compressive stress level, created cracks and microcracks sensitive to thermo-hygrometric conditions, provoking an increment of internal stress in the outer layers of the blocks, thus facilitating spalling. A deterioration process was therefore initiated, leading to a critical situation decades or centuries after the original action. This phenomenon, leading to near collapse, was observed by us in 1979, when following the removal of cladding blocks, a limit state situation was evident (fig. 8)

In 1703 another destructive earthquake occurred, again with its origin in the appenine region and the same energy characteristic as the one that occurred in 1349. Nevertheless damages were much less exstensive, only the ruin of an arch having been recorded. To understand the behaviour of the structure in this configuration, a new model has been prepared under the hypothesis that the most vulnerable part, the outer annular wall, had highly inefficient radial constraints. Results show a wave deformation of the attic level (fig. 9) both in the horizontal and vertical planes, and high vertical stresses in the pillars at the free edge of the surface, affected by an outward flexural action around the radial axis. The maximum flexural stress, $\sigma_v = 34.27$ KN/m^2, cannot be equilibrated by the dead-load stress. The annular horizontal stresses in the attic reach a maximum in the area of the minor axis ($\sigma_a = 12.1$ KN/m^2). As it can be seen the zones more stressed are the zones that a century later were affected by the large restoration works of Stern, Valadier, Salvi, and today the deformation provoked by the seismic action is still visible in part of the attic level (fig. 6).

According to the process outlined above, and to the frictional nature of the material, is likely that the high stress values resulting from the elastic analysis were not reached in the various elements in a istantaneus manner: more likely the damage phenomena slowly evolved toward the collapse, and their complete revelation was delayed up to forty years later, when, due to the spread state of ruin and incipient crash Benedetto XIV closed the monument and started its first restoration campaign.

3. ASSESSMENT OF THE CURRENT SAFETY LEVELS AND RESTORATION APPROACHS

As it has been seen in the previous paragraph the spatial distribution of structural alterations and the general state of conservation vary due to original oddities and are further accentuated by the train of events, so that today, in spite of the strenghtening works that took place in the last century, aimed at a global improvement of the structure performance, the safety levels also vary greatly.
Searching for the reasons why the three main interventions on the Colle Oppio side were realised, the Stern abutment (1807), the Valadier abutment (1825), Salvi's partial reconstruction of the third medium order and the system of radial tie-rods in the allignments around the imperial entrance, they appear to be attempts to stop an incipient collapse mechanism of the outer wall with characteristics very close to the f. e. model results. We have already seen how the outer edges of the surviving structure, where the constraints were lesser or inexistent, were the areas most under threat of collapse. The two abutments, with very different lay-outs and technologies involved, had the same aim of containing the annular thrust of the arches at the edge of the wall, limiting and preventing further development of vertical cracks and out of plumbs: both of them are connected to the original inner structure to recreate the collaboration along the radial directions. Their stiff and massive character highly modified the overall structural behaviour: having restrained its vertical edges, no longer allowed to move outward, deformations migrated to the area around the minor axis, whose bond between blocks had already been loosened. Outward movements, producing flexural stress in the lowest pillars, amplifying themselves because no tensile strength was available to counteract them, increased upto a point when Salvi's intervention was needed to prevent collapse.
These XVIII century restorations were all related to static stability, with no concern for dynamic actions. In fact, analysing their behaviour as part of the global structure under seismic actions, the abutments appear to be rather dangerous due to the difference in strength with regard to the original material, while also involving excitement of large masses. The worst result stems from actions orthogonally oriented to them; in the model analysed, connections in the radial direction are assumed to be active: the static situation is already quite different from the original one (fig. 10), the present configuration implying higher flexural stresses in the pillars of all orders (maximum eccentricity being up to 5 times higher than the original value); the seismic action, on a structure with fundamental natural frequencies 2 times smaller than the original one, greatly amplifies this phenomenon especially for the pillars of the third order where the stiffening contribution of the abutments is less and the connection with the inner rings are only partially realised (fig. 11). For those pillars flexural stresses produced by the earthquake are of the same order of magnitude as the static ones, therefore causing partialization of the cross sections (σ_v reaches 22 KN/m^2 versus -14.4 KN/m^2 of the dead load case). The attic portion has very low natural frequency these being caused by the low stiffness in the annular direction; stresses are of the same level as before but greater deformation and further sliding should be expected.
The study discussed above gives many indications of the criteria required to provide the monument with adequate safety levels and durability. The first task will be related to the deterioration process that affects many parts of the monument, for example the zone adjacent to the six pillars that were restored in 1979; it will be necessary to strengthen or replace some of the blocks. The second task is related to the vulnerability of the structure to seismic action: this inadequacy has increased throughout the centuries due to the loss of continuity, the separations formed between the elliptical walls, the out of plumb and the sliding of blocks. Consequently an improvement of the tensile resistance in both annular and vertical directions for the outer walls is required: this can be achieved by creating efficient circumpherential connections at the top of the wall and radial ties corresponding with the inner structure. In order to provide an efficient global behaviour, the region of interface between the original structure and the Stern and Valadier abutments also requires strengthening.
However, the historical value of the Colosseum obliges us to proceed with prudence in every intervention, and to avoid where possible further changes to the present form.

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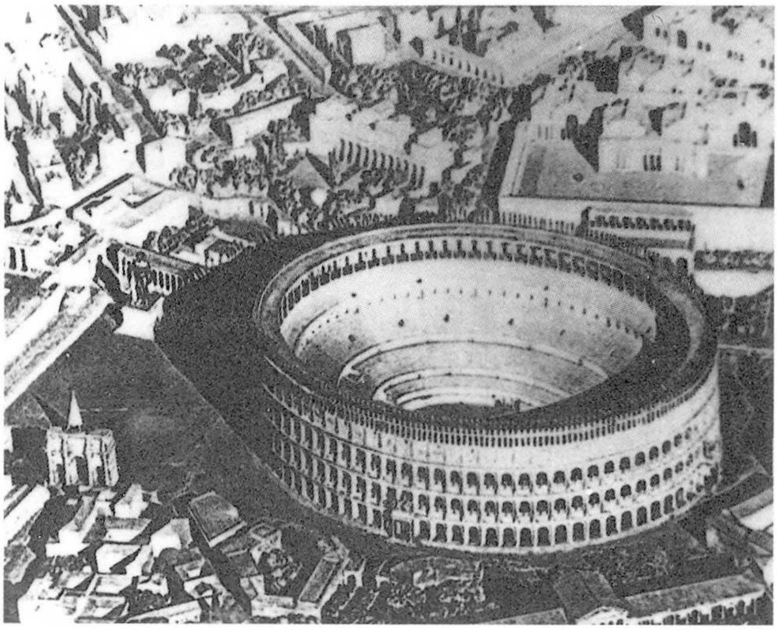

fig. 1 - Model from the plastic of "Roma at the time of the Empire"

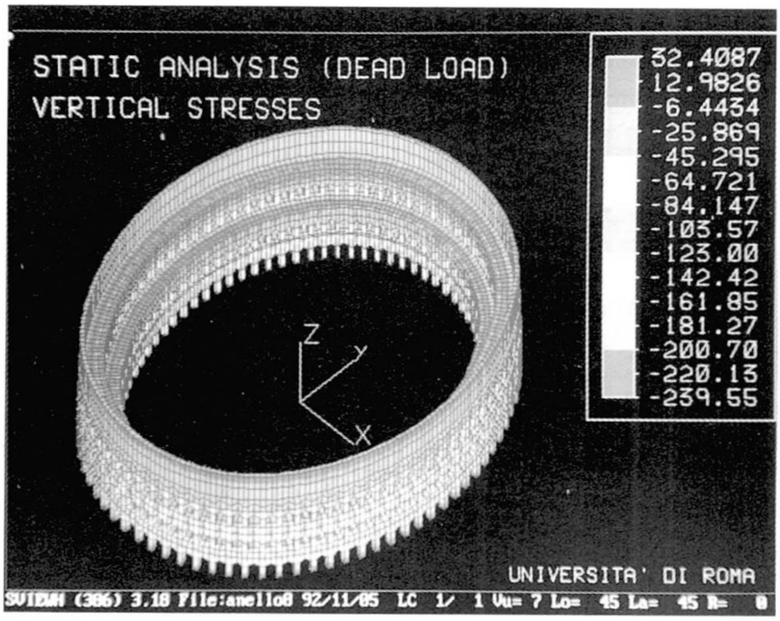

fig. 2 - Analytical model for the original configuration

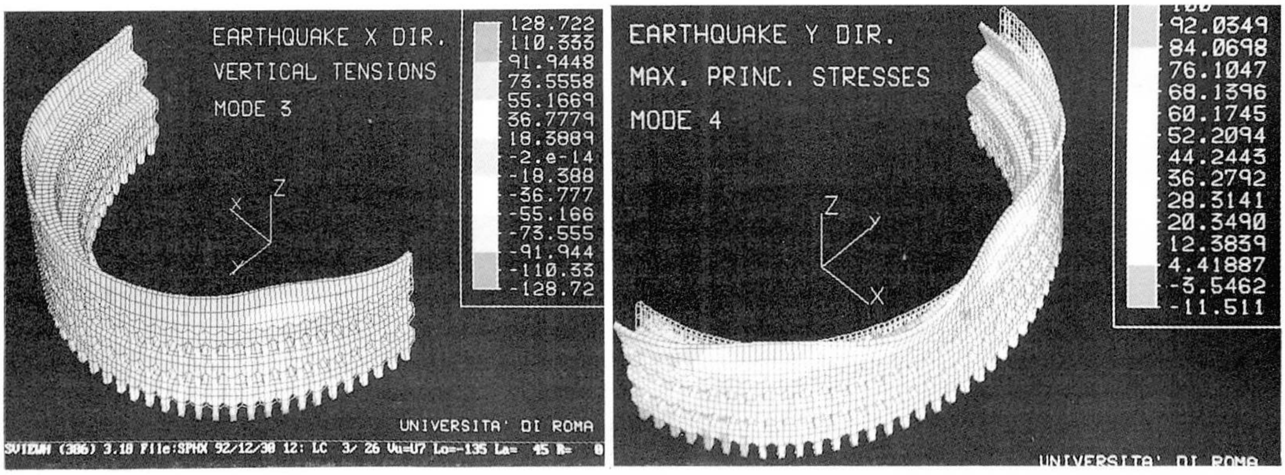

fig. 3 - 4 Response spectrum dynamic analysis for the original shape

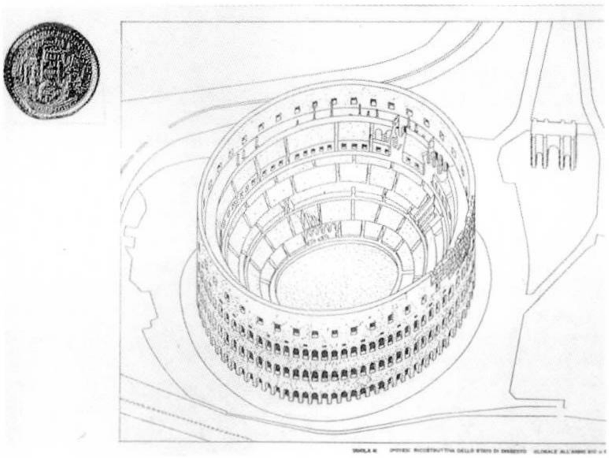
fig. 5 Hypotethical state of conservation after year 801

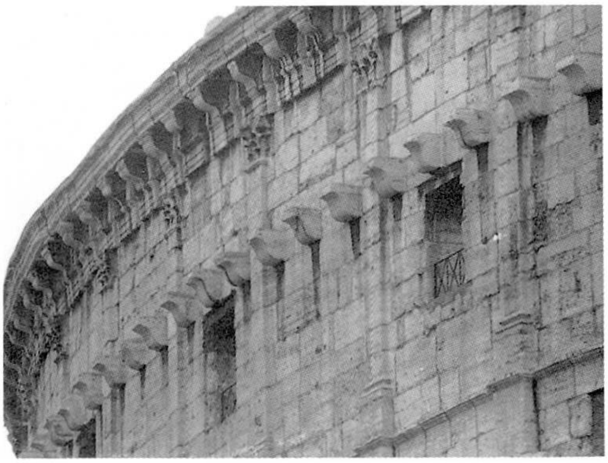
fig.6 Synusoidal deformation of the parapet.

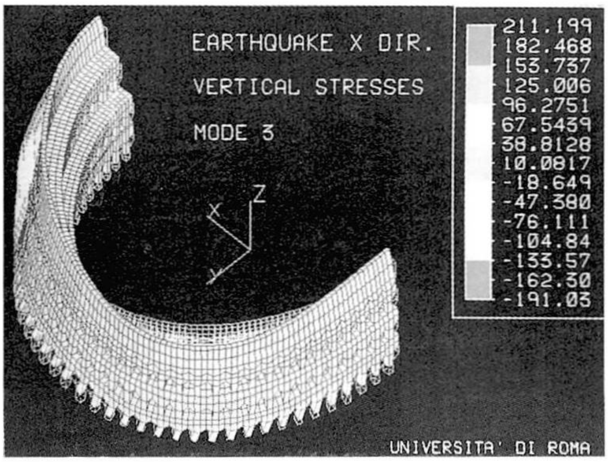

fig. 7 Spectrum response dynamic analysis simulating differentiated foundations


fig.8 State of the pillars on the Stern abutment side in 1979.

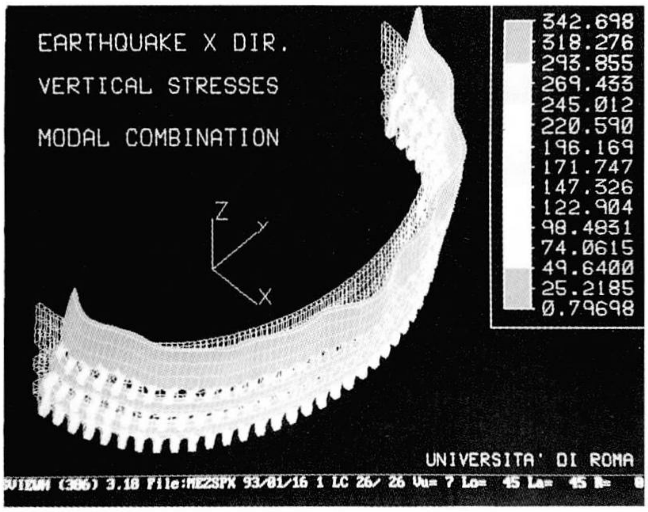

fig. 9 Analytical model in the 1703 configuration

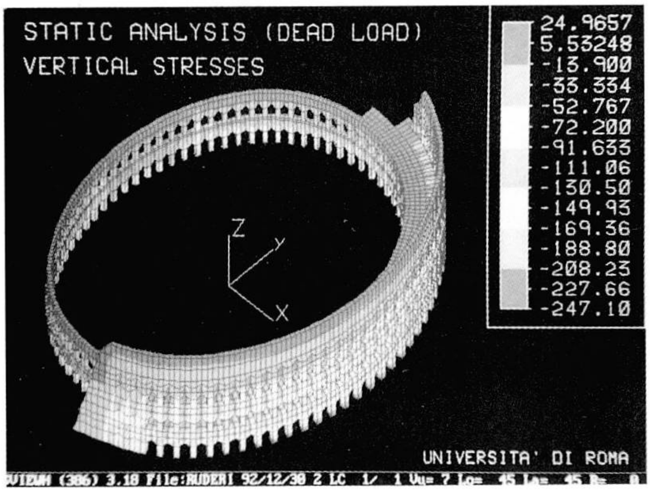

fig. 10 - Analytical model of the today configuration

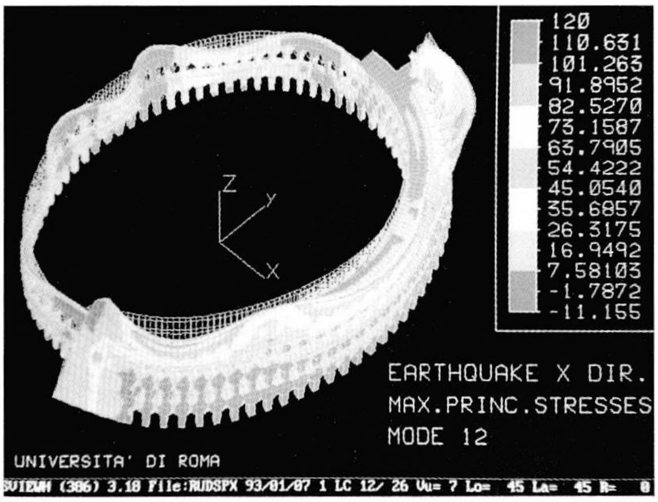

fig. 11 - Analytical model of the today configuration. Spectrum response dynamic analysis.

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